LLNL-PROC-675035

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July 22, 2015

SPIE Optical Engineering + Applications
San Diego, CA, United States
August 9, 2015 through August 13, 2015

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Multi-axis neutron imaging at the National Ignition Facility

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ABSTRACT

Inertial confinement fusion experiments at the National Ignition Facility (NIF) rely on a neutron imager to measure the 2D size and shape of the neutron-producing region in the burning deuterium-tritium plasma. Since the existing neutron imager is located on the equator of the NIF chamber, it provides only one view of the plasma, which complicates understanding the inherently three-dimensional nature of the implosion. Attempts to use x-ray images combined with the neutron image to improve our understanding of the 3D neutron-burn volume have proved to be inconsistent with the fuel mass. This result is understandable since neutrons and x-rays are not produced or propagated in the same manner. Thus, it is desirable to use multiple neutron imagers, and we are designing two neutron imagers on lines of sight that are nearly orthogonal to the current imager, one near the pole of the chamber and one near the equator, for fielding on the NIF in the next five years. In this paper, we will discuss the current designs, including the resolution, field of view and placement in the facility that will be required to use the three orthogonal neutron imagers to measure the neutron burn volume of plasmas at NIF. Prepared by LLNL under Contract DE-AC52-07NA27344.

Keywords: neutron imaging, National Ignition Facility, NIF, Inertial confinement fusion, ICF, burn volume

1. INTRODUCTION

The shape and size of the burning deuterium-tritium (DT) fuel volume are key parameters for understanding indirect-drive inertial confinement fusion (ICF) [1] experiments at the National Ignition Facility (NIF) [2, 3]. Since x-ray and neutron images of the imploded capsules at NIF have shown that the implosions can be asymmetric [4-7], a faithful reconstruction of the three-dimensional (3D) burn volume requires a minimum of three imaging measurements, preferably from near-orthogonal directions. At present, the NIF has only one neutron imager on the equator, so a direct neutron-only measurement of the 3D burn volume cannot be made. Attempts have been made to reconstruct or estimate the burn volume using one neutron image and two x-ray images, one from an equatorial x-ray imager on a line of sight (LOS) 123° away from the neutron imager and another from an x-ray imager on the pole of the chamber, but these images are sometimes mutually inconsistent, seriously compromising any estimate of the burning volume. For example, the equatorial x-ray image and existing neutron image often do not have the same relative orientation and overall shape, which leads to a large uncertainty in the derived volume. Furthermore, even when the different images are physically consistent, the enclosed, stagnated deuterium-tritium fuel mass estimates can be larger than the initially loaded fuel mass. This inconsistency is directly related to the weak constraints imposed on the burning core shape by the limited number of images available. Since the x-ray images are sensitively dependent upon the electron temperature, ablator composition and opacity, their relationship to the burn volume is indirect. Neutron images are much less sensitive to these effects. Thus, inconsistency between the x-ray and neutron images might be expected, and this uncertainty highlights the need for additional neutron imaging along three near orthogonal lines of sight at NIF.

Since it was commissioned at the NIF, the existing neutron imager on LOS 90-315 at the NIF, the Neutron Imaging System (NIS)[8], has been a standard diagnostic for NIF shots with deuterium-tritium fusion yields greater than 10^{14} neutrons. The NIS is a multi-aperture imager with micro-channel-plate gated intensifiers (MCPIs) that time gate the light from a fiber-scintillator array to produce two energy-resolved images. Since the neutrons penetrate the edges of the thick aperture, the apertures have spatially dependent point-spread functions, the effects of which are removed using Maximum Likelihood image reconstruction[5]. After image reconstruction, the resolution of the images is ~10 µm. The NIS has been extensively characterized[9] and used for more than one-hundred shots, and data from the imager has been used for a variety of experimental campaigns, including the high-foot implosion[7] and thin-shell high-foot[6] campaigns.

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Considering the performance of the NIS, it would seem rational to simply reproduce the existing system design on the polar line of sight and an additional equatorial line of sight. The existing NIS, however, has a line of sight greater than 28 meters long, which places its detector system outside the NIF target bay. To reproduce the system on the pole would require construction of expensive infrastructure on the roof of the building in addition to drilling new penetrations of the building radiation shielding. Thus shorter neutron imager designs that could be entirely enclosed in the NIF building are needed.

An additional issue is that the NIS relies on the Opposed Port Alignment System (OPAS) [10, 11] to align the pinhole aperture array. Due to the design of the NIF target chamber, which has pumping ports at its south pole, an OPAS-like system could not be placed to view a pinhole mounted on the polar diagnostic instrument manipulator (DIM) without either significant chamber modifications or creation of an added optical LOS along the neutron LOS. Moreover, the NIF facility is planning to transition to an Advanced Laser Tracking System (ATLAS) for alignment in the target chamber. Thus, any new design for a neutron imager will need to be designed to work with the ATLAS system for alignment.

In this paper, we will discuss the requirements for the new neutron imaging systems at NIF and detector limitations that drive the current length of the NIS. We will then describe our phased approach to the problem in which we will start with an energy-integrated detectors based on (n,p) conversion in polyethylene plates and image plates to allow rapid fielding and demonstration of the alignment methods before moving to gated-scintillator systems that allow energy resolution.

2. SYSTEM REQUIREMENTS

The fundamental system requirements are set by the need to image the unscattered (the primary 14.1-MeV neutron or hot-spot image) DT fusion neutrons and to image the neutrons that have down-scattered in the remaining cold fuel (the 6-12 MeV or down-scattered image). Since the hot-spot convergence ratios for ~2-mm diameter capsules are typically between 25 and 60, the systems are required to have 10-µm resolution with a 100-µm diameter field of view (FOV) for the unscattered-neutron image and a 150-µm FOV for the down-scattered-neutron image at unscattered-neutron yields between 10^{15} and 10^{19} neutrons. To accommodate larger sources such as direct-drive and indirect drive exploding pushers, 200-µm FOVs at the source are planned. Since the neutron apertures are arrays of pinholes or penumbral pinholes, subsets of the pinholes can form coded apertures and provide a larger effective field of view so that the individual pinholes do not necessarily have to cover the full field of view of the target.

The overall effective fields of view for the apertures also provide significant relief on the alignment of the aperture array. For the Maximum Likelihood image reconstruction, the centering of the axis of the apertures relative to the source must be known to better than ±25 µm in the horizontal and vertical dimensions of the source plane. Using the entire array of images, the source position for each shot may be determined from the obtained images[9], so the absolute alignment is unimportant as long as the FOV of the full array contains the FOV of the source.

3. DESIGN PHASES

Due to the cost and complexity of the designs, the new neutron imagers are being developed in four distinct design phases, Phase 1a and 1b and Phases 2a and 2b where “1” indicates a polar line of sight, “2” indicates an equatorial line

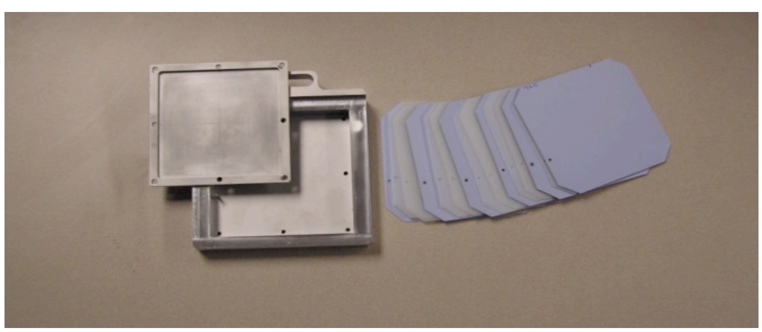
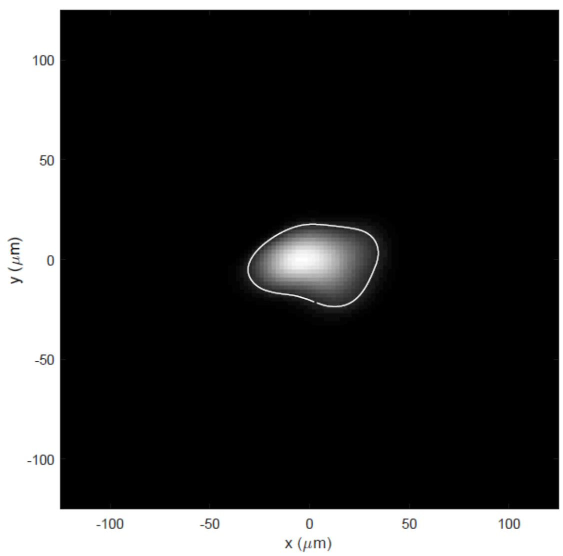


Figure 1 Image plate stack used for energy integrated neutron imaging. The stack consists of alternating image plates and 2-mm polyethylene sheets. Neutrons interact in the polyethylene producing (n,p) conversions, and the protons produced are detected by the phosphor-storage image plates, which are read out with a laser.

of sight, “a” indicates an energy integrated detector and “b” indicates and energy-resolved detector. Thus in Phase 1a, we will produce an energy-integrated imager on a near polar line of sight. The near-polar line-of sight was chosen for this first phase since it will provide a view along symmetry axis of the hohlraums that are used for indirect drive at NIF and is expected to provide more immediately useful information about the implosion symmetry than an additional equatorial line of sight. To simplify the initial phase, we will use an energy-integrated detector consisting of an alternating stack of 2-mm polyethylene plates and phosphor-storage image plates[12, 13], shown in Figure 1. In this detector, the neutrons interact in the polyethylene producing (n,p) conversions, and the protons then deposit their energy in the phosphor-storage image plates, which are read out later with a laser scanner. This detector was developed as part of an effort at NIF aimed at obtaining x-ray images on the same line of sight as the current NIS and was found to be sensitive enough for neutron imaging as shown in Figure 2.

In Phase 1b, the image plate based detector will be replaced with a gated detector, which will require additional development to obtain the desired detector resolution as discussed in Section 4. Phases 2a and 2b will be similar to Phases 1a and 1b but on an equatorial line of sight.



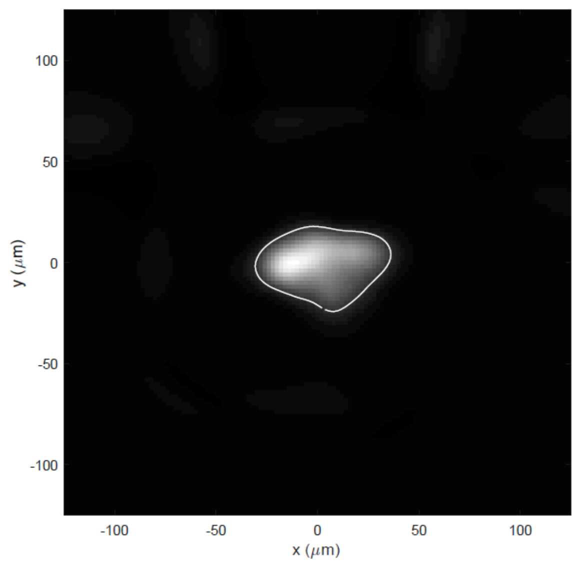


Figure 2 Reconstructed neutron images produced the on existing equatorial neutron imaging line of sight. On the left is the image of the 14.1 MeV neutrons from the NIS. On the right is the energy-integrated image obtained using a stack of polyethylene (n,p) converters and image plates placed in the NIS line of sight. White lines showing the 17% contour are shown on each image. As expected since the contribution to the energy-integrated image from down scattered neutrons is small, the images are similar and the differences are within the errors of the reconstructions.

4. DETECTOR RESOLUTION

The 28-m length of the existing NIS is required due to the need for high magnification (~76) and the low spatial resolution of the BCF-99-55 fiber scintillator, which has been measured to have an approximately Gaussian spatial response with a full width at half maximum of 1.1 mm for the fiber-coupled system[8]. Even with image reconstruction to remove some of the effects of the point-spread function of the pinhole array5, the detectors for the new systems will require significantly improved spatial resolution. To test the resolution of the Phase 1a detector, the alternating stack of 2-mm polyethylene plates and phosphor-storage image plates, we placed an image plate stack just outside one of the ports of the NIF chamber with a 3”-thick block of iron with a 0.5 meter radius on two sides in front of it and irradiated it with neutrons from a shot at NIF. The integration along one edge for this rolled-edge measurement is shown in Figure 3. Simulating the data required blurring the expected result with a Gaussian of the form $I(r) = I_0 \exp\left(r^2/2\sigma^2\right)$ where r is the spatial coordinate and σ = 275 μm. The full width at half-maximum of the Gaussian would be ~647 μm, a significant improvement over the existing NIS detector. Based on this measurement, we are proceeding with designs that have a 16.5-m line of sight with a standoff of the pinhole of 20 cm and a nominal magnification of -81.5.

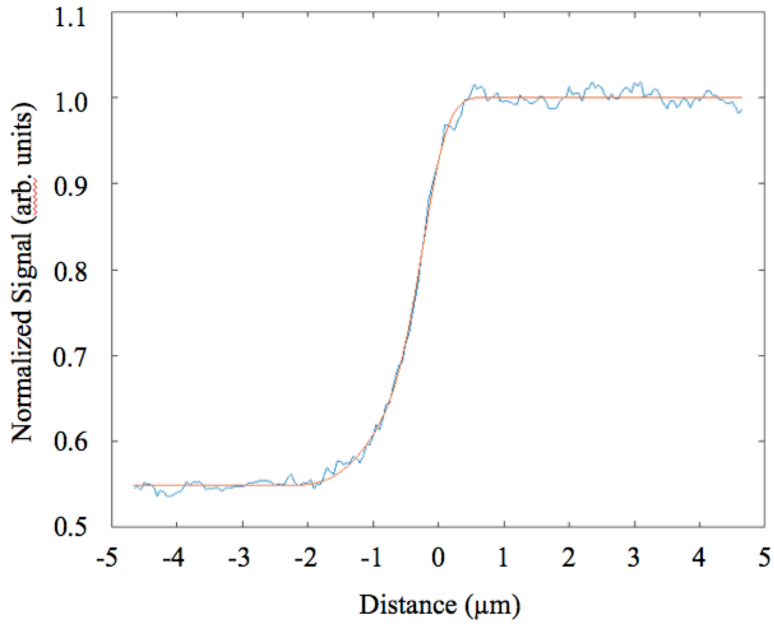


Figure 3 Measurement of the edge-spread function for a polyethylene/image plate stack detector. The signal is a line out across for a measurement of the transmission through a 3”-thick iron block with a 0.5-m rolled edge. The blue line is the measurement, and the red line is a model for the transmission with a 275-µm blur and the noise background included.

5. POLAR NEUTRON IMAGER DESIGN

For the near-polar imager, we are designing for LOS 5.75-225, which would allow placement of the detector near the roof in the rotunda of the target chamber building. The polar diagnostic insertion module (PDIM) on LOS 0-0 will hold the pinhole aperture array. Since the PDIM is also required to hold a Hardened Gated X-ray Detector (HGXD) [14], solid radiochemistry collectors and the x-ray pinholes for a planned dilation x-ray imager (DIXI) to supplement the existing DIXI [15, 16], the space and allowable weight for the pinhole array and its alignment actuators and fiducials is limited and still under design. The keep-out zone required for the incoming NIF laser beams also limits the space available.

6. APERTURE ARRAY DESIGN AND ALIGNMENT

The requirement for 10-µm resolution over a 200-µm FOV at yields as low 10^{15} neutrons places significant restrictions on the design of the aperture array. The pinholes must be small to obtain the desired resolution, but the small size of the pinhole limits the FOV and neutron signal at the detector. The small FOV and high-aspect ratio of an individual pinhole also makes alignment difficult unless an array of apertures is used to provide a larger effective field of view. The solution used for the existing NIS was to use 20 triangular tapers and three mini-penumbral pinholes, which provides an effective FOV of ~500 µm. This aperture was made by scribing either single-sided triangular tapers or penumbral pinholes in 20-cm long wedged layers of gold and clamping the aligned layers between two tungsten blocks[8, 9], and the same method of manufacture if not the exact same design is expected to be used for the polar imager.

Due to the high magnification of the current design and the relatively small fields of view of individual pinholes, the alignment of the aperture array is task that must be performed successfully on each shot. While the existing NIS uses and Opposed Port Alignment System (OPAS)[11], the new systems are expected to use an as yet unfielded Advanced Tracking Laser Alignment System (ATLAS) from FARO. ATLAS will use a laser tracker with spherically mounted retroreflectors (SMRs) on the objects to be aligned and is expected to have a number of advantages for alignment, including a larger

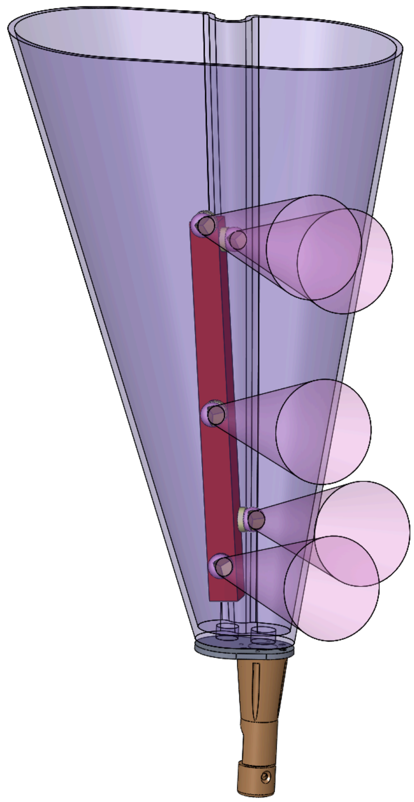


Figure 4 Conceptual design showing the neutron imaging pinhole array (20-cm long x 1.5 cm x 1.5 cm, shown in red) mounted vertically inside a shroud (blue-gray) to the left of the line of sight for an HGXD. The target would be 10-cm below the pinholes for the HGXD (gold). The SMRs for alignment (purple with conical extensions showing where clear lines of sight would be required to the laser tracker) would be mounted to the array or to the mounting structure that will be required to hold it.

field of view for measurement and the ability to make rapid automated measurements. Proper placement and metrology of a number of retro-reflectors is expected to be required for aligning the polar neutron imager, which will be mounted to the array itself or to its permanent mounting structure as shown conceptually in Figure 4. The accuracy of the metrology of the position of the SMRs with respect to the centerline and front and back planes of the body of the pinhole array is expected to be on the order of a few microns.

An important factor for the aperture design, however, is to determine what effective FOV for the overall aperture would allow high reliability for alignment. The 2σ (two standard deviation) single point uncertainty is also expected to be ~58 μm at 6 m from the tracker, which could be slightly less accurate than the performance of the OPAS. Assume this error for placement of the target and the front and back of the aperture array on the LOS from the nominal target position to the center of the detector. Also allow a 2σ error of 6 μm in the metrology of the retroreflectors relative to the front and back of the array and making the detector 24 mm larger in each dimension than the expected array of images at the detector. Under these assumptions, the combined FOV of the aperture array would need to be 700 μm in diameter to reach a 95% chance of alignment without impinging on the 200-μm reconstructed FOV of the images. To cover a 700-μm FOV with sufficient overlap of the images from the different pinholes could require a larger number of pinholes than are used for the current NIS, and we are actively investigating designs with ~64 pinholes, which is a design and manufacturing challenge.

7. CONCLUSIONS

The NIF neutron imaging team is actively designing two additional neutron imagers for lines of sight that are nearly orthogonal to the existing neutron imaging system. When constructed the systems are expected to provide images that will improve our understanding of the three-dimensional nature of the burning fuel with resolution of ~10 μm. We expect to build and field the imagers in a phased approach that will initially use large-area energy-integrated detectors based on image plates with (n,p) converters to reduce cost and alignment risk before development and installation of the more traditional energy-resolved systems.

We wish to thank Charles Cerjan for discussions on the burn volume and the NIF operations team who make the facility and experiments work. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344.

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